PB86-120227

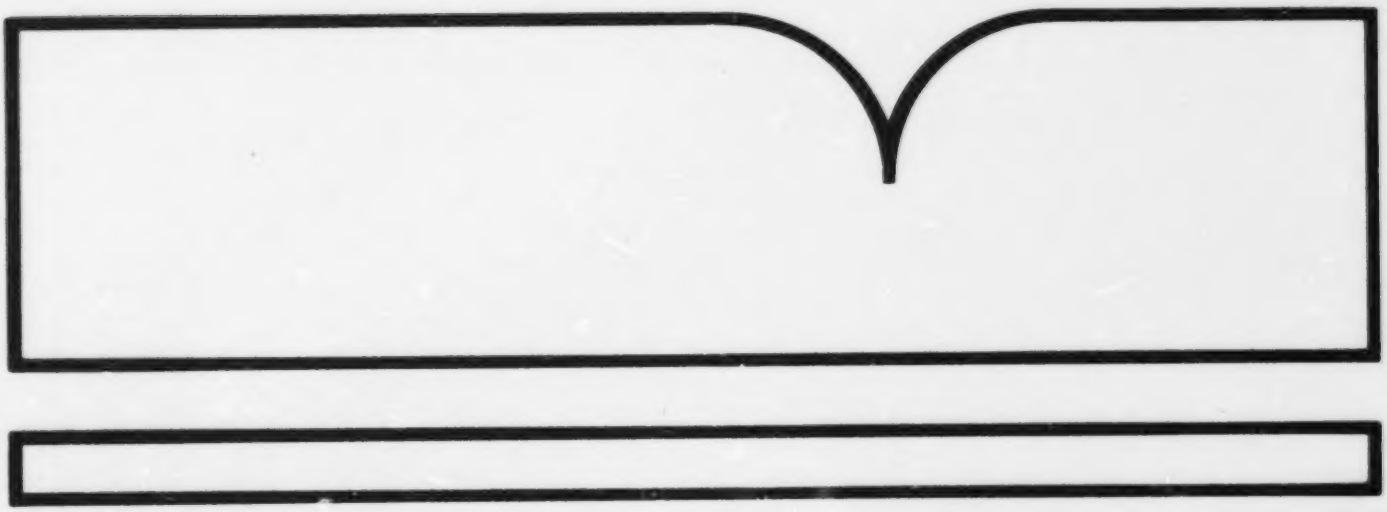
Characterization of Emissions of PAH's (Polynuclear Aromatic Hydrocarbon) from Residential Coal-Fired Space Heaters

Vermont State Agency of Environmental Conservation, Montpelier

Prepared for

Environmental Protection Agency
Research Triangle Park, NC

Oct 85



U.S. Department of Commerce
National Technical Information Service
NTIS

PB86-120227

EPA/600/D-85/243
October 1985

CHARACTERIZATION OF EMISSIONS OF PAH'S FROM RESIDENTIAL COAL-FIRED SPACE HEATERS

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EPA Contract 68-02-3169

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SPRINGFIELD, VA. 22161

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO.	2.	3. RECIPIENT'S ACCESSION NO.
EPA/600/D-85/243		

4. TITLE AND SUBTITLE	5. REPORT DATE
Characterization of Emissions of PAH's from Residential Coal-fired Space Heaters	October 1985
	6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) C. R. Sanborn (Vermont Agency of Environmental Conservation; M. Cooke and W. Bresler (Battelle-Columbus Labs); and M. C. Osborne (EPA/AEERL)	8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Battelle-Columbus Laboratories Columbus, Ohio 43201	10. PROGRAM ELEMENT NO.
	11. CONTRACT/GRANT NO. 68-02-3169, Task 29
12. SPONSORING AGENCY NAME AND ADDRESS EPA, Office of Research and Development Air and Energy Engineering Research Laboratory Research Triangle Park, NC 27711	13. TYPE OF REPORT AND PERIOD COVERED Published Paper; 14. SPONSORING AGENCY CODE EPA/600/13

15. SUPPLEMENTARY NOTES AEERL project officer is Michael C. Osborne, Mail Drop 63, 919/541-4113.

16. ABSTRACT The paper gives results of a joint emissions testing and analysis program--the U. S. EPA and the State of Vermont--to determine polynuclear aromatic hydrocarbon (PAH), particulate, sulfur dioxide (SO_2), and carbon monoxide (CO) emissions from two coal-fired residential space heaters. One had a magazine type feed system; and the other, a batch loader. Anthracite and bituminous coal were burned in each stove at rates representative of normal homeowner use. A modified EPA Method 5 train (with an XAD-2 resin trap) was used to collect PAH and particulate samples. Six particulate tests were run (three each for bituminous and anthracite). Emissions of particulates, extractable organics, PAH, and volatiles were higher for bituminous coal than for anthracite. The style of the stove, type of fuel, and burn rate all affect emissions; therefore, when comparing overall emissions from the two stove styles, it was not clear which stove was the less polluting (i.e., more efficient). SO_2 emissions depend on both the firebox temperature and the alkalinity of the ash and are, therefore, expected to vary accordingly from test to test and from stove to stove. (Values reported in the study represent a very small data base; thus should be considered a contribution to the literature in the field, instead of a comprehensive evaluation of these combustion systems.)

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group	
Pollution	Analyzing	Pollution Control	13B	14B
Aromatic Polycyclic Hydrocarbons	Particles	Stationary Sources		14G
	Dust	Particulate	07C	11G
Space Heaters	Aerosols		13A	07D
Coal	Sulfur Dioxide		21D	07B
Combustion	Carbon Monoxide		21B	

18. DISTRIBUTION STATEMENT	19. SECURITY CLASS *(This Report)*	21. NO. OF PAGES
Release to Public	Unclassified	18
	20. SECURITY CLASS *(This page)* Unclassified	22. PRICE

EPA Form 2220-1 (9-73)

NOTICE

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Introduction:

A joint emissions testing and analysis program was conducted by the U.S. Environmental Protection Agency and the State of Vermont to determine polynuclear aromatic hydrocarbon (PAH), particulate, sulfur dioxide (SO_2), and carbon monoxide (CO) emissions from two coal-fired residential space heaters. Testing was conducted in October 1982 at a test facility in Barre, Vermont. One space heater had a magazine type feed system while the other was a batch loader. Anthracite and bituminous coal were burnt in each stove at burning rates felt to be representative of normal homeowner usage. A modified EPA Method 5 train (utilizing an XAD-2 resin trap) was used to collect PAH and particulate samples. A total of six particulate tests were run (three each for bituminous and anthracite). The field samples were submitted to Battelle-Columbus Laboratories for both quantification and qualification of the PAH emissions as well as particulate emissions, extractable organics, and volatiles.

Analysis included fixed combustion gases, condensible organics, Method 5 particulates, principal volatile compound screening by gas mass spectrometry (GMS), and PAH analysis by high resolution gas chromatograph/mass spectrometry (GC/MS).

Experimental Methods:

The two stoves were started up and operated in a manner dictated by the stove design and type of fuel being used. These procedures are described in detail in the latter part of this section. Each stove was tested with bituminous and anthracite coal to evaluate the effect of the two fuels on emissions. Stove B was tested at both a high and low burn rate, while Stove C was tested at a moderate burn rate.

The stove to be tested was placed on a set of beam scales, such that the weight of fuel used during the test period could be accurately determined. Each stove is designed to operate with a 0.15m diameter round flue pipe. The flue pipe extended vertically up into a 0.18m diameter elbow, which was 1.2m from the chimney. The .03m space around the vertical flue pipe allowed the stove to be weighed without being affected by the weight of the remaining flue pipe and testing equipment. During actual sampling, the .03m gap was sealed with an aluminum foil collar.

All flue gas samples for Orsat analysis were taken upstream of this loose connection. Gas samples for particulate and SO_2 analysis were taken in the horizontal 0.18m pipe. Draft temperature measurements were taken downstream of the sampling probes.

Stove Design and Operating Specifics

Stove B (Coal Stove)

This stove was a magazine style stove, designed to burn "pea" sized anthracite or "nut" bituminous coal. The only fuel that was actually burning was the fuel which was on the grates. When burning anthracite, the stove was designed such that the exhaust gases passed out of the combustion chamber at both ends of the grates, and did not pass through the magazine of fuel. In order to burn bituminous coal in this stove, a different magazine was required. With the bituminous magazine in use, the exhaust gases still exited at either end of the grates, but some of the gases first passed through the magazine of fuel. This allowed the volatiles to be released at a slower rate and, as they were released from the stored fuel, to be brought into the firebox where they should be combusted.

Primary air was controlled by an automatic damper system. No secondary combustion air was supplied when burning anthracite; for bituminous coal, secondary combustion was supplied along the front edge of the grates.

A coal fire was started and the magazine filled (with 11-23 kg of coal) approximately 2-3 hr prior to the start of emission testing. This allowed the stove to reach a normal operating temperature and the fire to stabilize. The tests for each fuel were conducted under both a "high" burn rate (approximately 1.4 kg/hr for bituminous and 1.9 kg/hr for anthracite) and a "low" burn rate (0.75 kg/hr for bituminous and 0.67 kg/hr for anthracite). Each test was conducted over approximately a 2 hr period. Table I contains a summary of the test parameters for each test.

Stove C ("Wood" Stove)

This was designed as a batch feed type stove, with manual control for the secondary air, and automatic controls (bimetallic strip) for the primary air inlet. The firebox will hold approximately 7-9 kg of either "pea sized" anthracite or "stoker sized" bituminous coal. The secondary air is partially preheated (approximately 200°C) before it enters the firebox along the back wall.

The primary air damper must always be at least half open in order to ensure that a sufficient amount of air is available for combustion. The secondary air inlet was left in the fully open position for all testing.

This stove can also be used as a wood stove by removing the coal grates and replacing them with the wood grates.

As with Stove B, a fire was started in the stove 2-3 hours prior to the start of testing. A new charge of coal was added to the firebox immediately prior to the start of each test.

TABLE I. STOVE AND SAMPLING PARAMETERS

Stove Parameters	Stove B - Coal Stoves				Stove C - Wood Stove	
	Bituminous High Burn Rate	Anthracite High Burn Rate	Bituminous Low Burn Rate	Anthracite Low Burn Rate	Bituminous Low Burn Rate	Anthracite Low Burn Rate
Burn Rate, kg/hr (lb/hr)(a)	1.2 (2.8)	1.9 (4.2)	0.8 (1.9)	0.7 (1.5)	1.2 (2.7)	0.9 (2.0)
Mean Stack Temperature, °C(°F)(b)	270 (520)	250 (480)	220 (420)	140 (278)	160 (315)	140 (280)
Sampling Time, min.	120	120	150	155	155	155
Stack Water, percent	1.8	3.5	1.8	1.6	1.9	2.3
Stack Oxygen, percent(c)	13	10	17	17	14	13
Stack Carbon Dioxide, percent(c)	6	10	4	3	6	7
Stack Carbon Monoxide, percent(c)	0.6	0.6	0.2	0.0	0.4	0.4
Method 5 Volume (dry), SCM (SCF)	1.8 (64)	1.9 (68)	2.0 (70)	2.4 (85)	2.3 (8.1)	2.5 (87)
Total Stack Discharge, Q, SCM (SCF)	64 (2,300)	58 (2,050)	72 (2,500)	80 (2,800)	67 (2,400)	44 (1,600)

(a) Averaged over total test.
(b) At Method 5 probe.
(c) Values determined by ORSAT technique.

The stove was operated at what was considered a "moderate" burn rate (0.9 kg/hr for anthracite and 1.2 kg/hr for bituminous). See Table I for a summary of test parameters.

During the combustion of bituminous coal, the volatile matter from the new charge of coal (when placed on an established bed) was burnt/driven off fairly rapidly (within half an hour).

Sampling Procedures

Sulfur Dioxide

For each particulate test conducted, at least one SO_2 test was conducted simultaneously using EPA reference Method 6. The SO_2 test was conducted over a 20 minute period with the average sample size being .028 DSCM of flue gas. The test train used a solution of 3% hydrogen peroxide to absorb the SO_2, preceded by an impinger packed with glass wool and 80% isopropyl alcohol to trap any sulfuric acid.

At the conclusion of the test, the glassware following the isopropyl-alcohol filled impinger was rinsed with distilled water, and the rinse placed in a sample bottle along with the peroxide solution. This sample was then diluted to a volume of 100 ml and titrated with barium perchlorate to determine the SO_2 concentration.

An additional sample was also collected using an evacuated sample bulb. (See description under Volatile Organics, below.)

Volatile Organics

Samples were collected for fixed gas and volatile organics analysis using evacuated glass bulbs. Three liter glass sampling bulbs were prepared at Battelle by evacuating to approximately 0.000001 torr pressure and heated to drive off residual moisture. After preparation, the sample bulbs were wrapped with foam insulation and shipped to the experimental site in Vermont. The gas samples were taken by inserting a stainless steel probe through a sample port. A sample was collected by opening the stopcock on the evacuated sample bulb during steady state combustion.

Flue Gas

An integrated sample of flue gas was collected over the duration of the particulate test. At the completion of the test the gas sample was analyzed using an Orsat analyzer for percent CO_2, O_2, and CO. Additionally, 15 minutes into the test an evacuated flask was used to collect a single grab sample of the flue gas. (Description of sampling flasks is contained under Volatile Organics, above.)

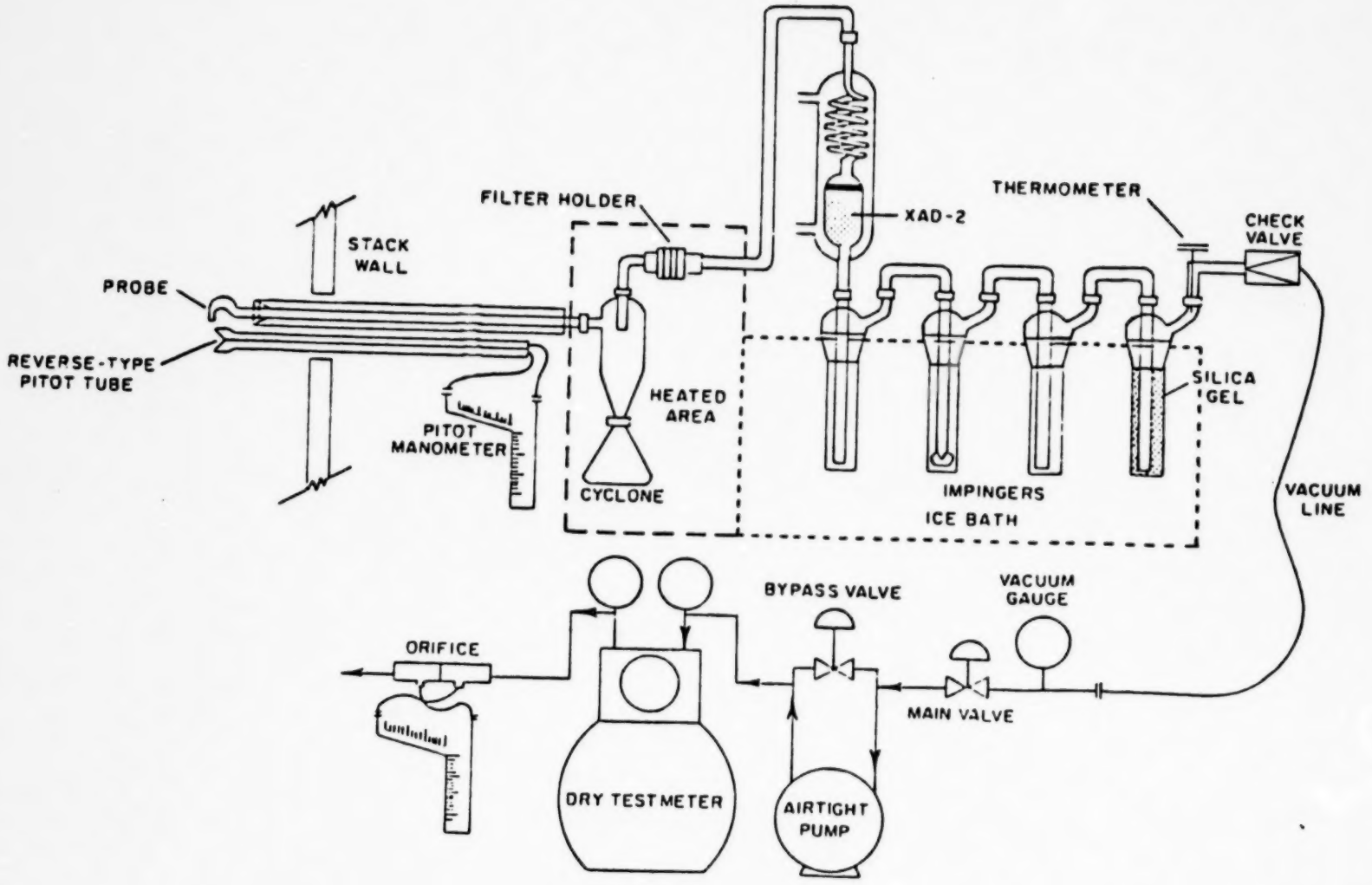

Figure 1. Particulate Sampling Train - Modified Method 5

Particulates and PAH

All testing for particulates was done using the Modified EPA reference Method 5 sample train, shown in Figure 1. Three determinations were made on the Modified Method 5 sample: condensible organics, particulate matter, and PAH. The Method 5 sampling train separates the sample into a particulate fraction in the heated probe and filter section, and a semivolatile organics fraction which collects on the resin. The XAD-2 resin material was extracted along with the particulate-laden filter in a Soxhlet extractor using methylene chloride. The filter was re-extracted separately with benzene to remove PAH compounds not extracted by methylene chloride. The resin-filter extracts were combined with the extracted aqueous impinger samples to produce a combined organics sample. The combined extract was analyzed by gas chromatography and gravimetry to determine condensible organics. This extract was also used for PAH analyses.

ANALYTICAL PROCEDURES

Fuel analysis:

An analysis of the fuel used in this study is contained in Table II. Due to the low values reported for percent oxygen and sulfur on both of the anthracite coal samples, parts of the analysis were redone and the low values were confirmed.

TABLE II. FUEL PARAMETERS

	Anthracite (Pea)	Bituminous (Nut)	Bituminous (Stoker)
Ultimate Analyses			
Carbon, percent	85.8	79.1	80.6
Hydrogen, percent	1.9	5.2	5.3
Nitrogen, percent	0.7	1.5	1.6
Oxygen, percent	0.1	6.9	4.9
Sulfur, percent	0.4	0.8	0.8
Ash, percent	8.9	3.2	5.5
Proximate Analyses			
Fixed Carbon, percent	85.6	56.5	56.2
Volatiles, percent	3.3	37.0	37.0
Moisture, percent	2.2	3.3	1.3
Heating value, dry basis, ash free, J/g	34,634	35,099	33,472

The bituminous coal, which was used, can be classified as high volatile, Class A, low ash, and low sulfur. The anthracite is low sulfur with an average amount of ash. Although the anthracite has a higher ash content than the bituminous, it has a much lower volatile content. Due to the low flue gas velocity, very little if any ash is carried out of the firebox of residential coal stoves by the flue gases; thus, the volatile content is of more concern than the ash content when coal is used in residential space heaters. Unburnt volatile matter may represent a significant portion of the particulate emissions, making a low volatile coal the more desirable fuel.

Gas Analyses

Fixed gas analyses were performed on the glass bulb samples. Samples were analyzed using a combination of mass spectrometry and three gas chromatographic techniques. A Consolidated Electrodynamics Corporation, Model 21-620, mass spectrometer was used for a general analysis from mass 2 to 100. Since the mass spectrometer does not separate CO and nitrogen the CO was determined using an Aerograph, Model 202, gas chromatograph with a molecular sieve column and a thermal conductivity detector.

Low molecular weight hydrocarbons and sulfur gases were determined using a Varian, Model 3700, gas chromatograph. The hydrocarbon analysis employed a Poropak Q column and flame ionization detector, and the sulfur gases were separated on a Supelco S column and detected with a flame photometric detector.

Condensible Organics Analyses

Condensible organics were measured by extracting the Method 5 particulates and the XAD-2 resin bed with methylene chloride and performing a gravimetric analysis (GRAV) on the extracts. This procedure is described in EPA's Level 1 manual for characterization of source discharges[1]. The gravimetric analysis measures the mass of extracted material. This analysis does not measure volatile species; in fact, most volatiles are lost by the Method 5 sampling train. The evacuated gas bulbs are useful in estimating principal volatile organics.

PAH Analyses

The filter/resin extraction yielded two extracts: a methylene chloride extract which contained most of the organic burden, and a benzene extract which contained much of the PAH. The combined extracts were reduced to a convenient volume by a Kuderna-Danish concentrator. The PAH compounds were then isolated by liquid chromatography using silica gel to remove interfering species. The column was packed (methylene chloride slurry) with 10 g of 100-200 mesh silica gel and washed with 40 ml of petroleum ether. A 25 ml fraction of petroleum ether was collected and discarded. The PAH were eluted with 75 ml of 20 percent methylene chloride in petroleum ether, followed by 30 ml of 50 percent methylene chloride in petroleum ether. The volume of the PAH fraction was reduced to about 1 ml by use of a Kuderna-Danish concentrator and to a final 0.5 ml by directing a gentle stream of nitrogen across the top of the sample. An internal standard (9-phenyl-anthracene) was spiked into the extract at this point.

The analytical scheme involved a glass capillary GC/MS procedure which separates many of the PAH isomers (including benzo(a)pyrene and benzo(e)pyrene) with only one chromatographic run. A 30 m SE-52 capillary column was directly coupled to the mass spectrometer via a glass capillary transfer line. The gas chromatograph was equipped with a Grob-type injector enabling splitless injections. The column was temperature programmed from 160 to 320°C at 4°C/minute. Injector temperature was 300°C, while the transfer line was held at 315°C.

Compounds such as coronene and dibenzopyrenes with boiling points above 520°C are eluted as sharp peaks. Close to baseline separation is achieved for isomeric compounds such as phenanthrene/anthracene, benzo(a)anthracene/chrysene, and benzo(a) pyrene/benzo(e)pyrene.

In the GC/MS analysis, sensitivity was improved by the use of single ion monitoring. The molecular ions of up to three compounds of interest were simultaneously monitored. Quantification was achieved by ratioing the ion current of the molecular ion of interest to that of the differences in ionization efficiencies of the compounds and the internal standard. The use of single ion monitoring minimized interferences from fragmentation of extraneous compounds which may not have been removed during the liquid chromatographic cleanup. Since the coal extracts were heavily loaded with organics, the silica gel cleanup and use of single ion monitoring were necessary.

Results

The stove operation data show that burn rates varied between 0.7 and 1.9 kg/hr, and typical gas discharge volumes varied between 44 and 80 m^3 as shown in Table I, which gives general test and stove operating parameters. The stoker grade bituminous coal was only used to test Stove C, the modified "wood" stove. Nut grade bituminous and pea grade anthracite were used in all other tests.

The effect of fuel type is clearly seen in the particulate discharge levels and condensible organics concentrations shown in Table III. In every case the bituminous coal gave much higher emission levels than anthracite. This is expected from the two coal types, but the magnitude of the differences in emission levels between the two coals is surprising.

In all cases the particulate and extractable organic emissions were higher for the combustion of bituminous coal than for anthracite coal. Based on additional emission testing conducted by the Vermont Agency of Environmental Conservation, it has been found that particulate emissions from the combustion of anthracite coal are not dependant upon the burn rate or the burn cycle. For bituminous coal the particulate and extractable organic emissions are dependant upon the burn cycle, which in turn is a factor of the stove design, fuel loading techniques, and the volatile content of the coal. The volatile matter from the bituminous coal is driven off as new fuel comes in contact with the burning bed. This stage creates a high emission rate, which drops off rapidly as the volatiles are released. For the latter portion of the burn cycle, where only the fixed carbon remains, the particulate emissions are as low as those from anthracite coal.

Testing conducted for this program encompassed an entire bituminous burn cycle for each test.

TABLE III. PARTICULATE AND EXTRACTABLE ORGANIC EMISSIONS

Stove	Coal	Burn Rate, kg/hr	Method 5[a] Particulates g/kg (mg/SCM)	Extractable[b] Organics g/kg (mg/SCM)	Carbon Monoxide g/kg (mg/SCM)
B-Coal	Bituminous	High (1.2)	10.7 (458)	2.2 (96)	166.7 (7135)
B-Coal	Anthracite	High (1.9)	0.1 (8)	0.05 (3)	122.0 (9760)
B-Coal	Bituminous	Low (0.8)	7.0 (176)	5.1 (128)	93.7 (2356)
B-Coal	Anthracite	Low (0.7)	0.3 (6)	0.1 (2)	59.5 (1190)
C-Modified Wood	Bituminous	Moderate (1.2)	4.9 (197)	1.6 (66)	116.8 (4696)
C-Modified Wood	Anthracite	Low (0.9)	0.2 (8)	0.2 (8)	227.8 (9112)

(a) Blank value determined, 0.0000 +/- 0.2 ng.
(b) GRAV only on XAD-2 extract.

Condensible organics are measured by extracting both the Method 5 filterable particulates and the XAD-2 resin bed with methylene chloride, then performing a total chromatographable organics (TCO) analysis, followed by a gravimetric analysis (GRAV) of the extracts. These two procedures are described in EPA's Level 1 manual for characterization of source discharges[1]. TCO is performed by summing the estimated responses of organic compounds with boiling points between 100 and 300°C. The gravimetric analysis measures the mass of extracted material with boiling points above 300°C. This analysis does not measure volatile species; in fact, most volatiles are lost by the Method 5 sampling train. The evacuated gas bulbs are useful in estimating principal volatile organics. The results of the volatiles analyses are shown in Table IV. For most compounds the sensitivity of gas mass spectrometry and gas chromatography with selective detectors is about 1-50 ppm (V/V).

TABLE IV. PRINCIPAL VOLATILE EMISSIONS, PPM (V/V)

	Stove B - Coal Stoves				Stove C - "Wood" Stove	
	High Burn		Low Burn			
	Anthracite	Bituminous	Anthracite	Bituminous	Anthracite	Bituminous
Methane	100	210	100	90	630	95
Ethene	1	722	0.2	1000	0.8	61
Ethane	1	2	--	--	2	--
Propene	--	2	--	--	--	0.4
Propane	--	--	--	--	2	--
p-Butene	--	--	--	3	--	--
SO_2	350	208	290	300	25	430
COS	--	--	--	3	23	1
CS_2	--	--	0.2	--	--	0.3
H_2S	--	--	--	--	6	--
NO_x	--	--	--	--	100	160

The results of anthracite tests show that Stove C, the modified "wood" stove, had higher methane emissions than Stove B, the coal stove. Stove B, the coal stove, generated much higher SO_2 levels than the "wood" stove, by a factor of 10, when burning anthracite. It has been determined from other SO_2 tests conducted on coal stoves by the Agency of Environmental Conservation that the SO_2 emissions are dependant upon stove type, burn rate, and the point in the burn cycle that the test was taken. Long term testing on both of these stoves has shown the emission of SO_2 from the combustion of anthracite coal to be very similar (5.2 g/kg for Stove B, and 5.7 g/kg for Stove C).

In tests with bituminous fuel Stove B, the coal stove, had much higher levels of methane and ethene than Stove C, the modified multifuel stove designed primarily for wood burning. The "wood" stove had higher levels of SO_2. Comparing the SO_2 data from this study with results of earlier EPA coal stove tests is very interesting. The industrial coal stoker boiler study firing bituminous coal[2] reported SO_x levels of 90-490 g/kg fuel-dry basis (180-970 lb/ton) with a mean of 227 g/kg (450 lb/ton) for 11 stokers tested, with 21 coal/fuel combinations.

During tests of stoker fed residential units,[3] SO_x was measured at 3-15 g/kg (6-30 lb/ton) for 10 tests with a mean of 9.5 g/kg (19 lb/ton). Bituminous coal was used in both studies, and each study showed a linear relationship between available fuel sulfur and SO_x emissions. In this study the three bituminous tests yielded values of 13 g/kg (fuel basis-dry-ash free) for Stove B, the high burn rate coal stove; 32 g/kg for the companion low burn rate test; and 29 g/kg for Stove C, the modified "wood" stove burning bituminous coal. Thus the residential units tend to produce lower SO_2 levels than larger industrial units. This is probably caused by the higher grate heat and more efficient combustion which is effective in releasing fuel bound sulfur and oxidizing it to volatile oxides in the industrial stoker boilers. Analysis of the coal ash from this study is being conducted by EPA to verify that they did in fact remain with the ash.

PAH emissions from coal combustion sources were summarized in 1967 in a classical paper by Hangebrauck, von Lemden, and Meeker.[4] These researchers graphically illustrated relative PAH emissions from several sources by using BaP as a key indicator compound. They reported BaP concentrations as a function of gross heat input to the furnace. Thus, large utility furnaces with very high grate temperatures, secondary air, and sufficient excess air, produce far less BaP per unit of fuel burned than residential units. Even though Hangebrauck et al. summarized data from the 1960s, the relationship of PAH emissions to combustion efficiency is still valid and has been verified many times. The Vermont study provided an opportunity to measure specific PAH compounds including BaP with modern analytical techniques and good quality control procedures.

The emission data for a representative series of PAH compounds are given in Table V. The magnitude of PAH emissions can be compared between sources by using consistent units. One Electric Power Research Institute study has suggested using ng/J x 10^{-5} as a standard unit for coal combustion.[5] Several sources including coal- and wood-fired residential units are compared in Table VI[6] using this unit as a basis for comparison. Residential coal combustion (using bituminous coal) shows the highest emissions of BaP relative to other coal-burning combustion systems compared. This observation is consistent with the Hangebrauck curve. Anthracite fuel was found to generate far lower BaP emissions than bituminous coal in equivalent appliances. BaP levels firing anthracite average lower by about 700 ng/J x 10^{-5} less than bituminous tests and about 16,000 ng/J x 10^{-5} less than reported wood combustion tests having the EPRI comparison unit. Higher BaP emission levels than found for residential bituminous-fired space heating have been reported (e.g., coal gasification);[7] however, the magnitude of the discharges found in the Vermont study together with high particulates and SO_x cause concern about the widespread use of bituminous coal for residential space heating.

TABLE V. POLYNUCLEAR AROMATIC HYDROCARBON EMISSIONS, µg/SCM

	Stove B - Coal Stoves				Stove C - "Wood" Stove	
	High Burn Rate		Low Burn Rate		Moderate Burn Rate	
	Ant.	Bit.	Ant.	Bit.	Ant.	Bit.
Naphthalene	5.3	830	0.08	210	14.(a)	>330(a)
Acenaphthene	0.94	120	0.12	19	0.82	70
Acenaphthylene	0.99	1100	0.12	16	6.3	>330(a)
Fluorene	0.89	210	0.08	90	1.2	210
Phenanthrene	11.	780	0.81	180	9.0	>330(a)
Anthracene	1.2	210	0.08	100	0.9	160
Fluoranthene	8.7	360	0.85	76	4.7	270
Pyrene	6.3	210	0.48	69	3.7	190
Benzo(a) anthracene	5.4	130	0.12	46	1.1	170
Chrysene	5.9	150	0.20	37	1.5	140
Benzo(k) fluoranthene	0.68	190	0.12	92	1.3	280
Benzo(e)pyrene	0.16	100	0.04	38	0.30	85
Benzo(a)pyrene	0.10	110	0.08	52	0.17	120
Perylene	0.02	13	0.02	5	0.04	16
Indeno(123-cd) perylene	0.37	14	0.04	36	0.17	150
Benzo(g,h,i) perylene	0.31	49	0.04	24	0.09	72
Anthanthrene	0.005	4	0.01	7	0.02	27
Coronene	0.21	60	0.01	9	0.13	42

(a) Saturated.

TABLE VI. BENZO(A)PYRENE EMISSIONS, 10^{-5} ng/J

Residential Stoves				
Wood	Bituminous (This Study)	Anthracite (This Study)	Industrial Units Bituminous-Fired	Utilities Oil-Fired
1.8×10^5	7.6×10^3	11	7 (5, a) (6, b)	0.04 (5, c)
			2	

[a] Reference 5, Table 3-1, page 3-3, power plants.
[b] Reference 6, bituminous-fired industrial stoker boilers.
[c] Reference 5, Table 3-5, page 3-9.

In other tests conducted by the Agency of Environmental Conservation on these two stoves, it has been found that the emission rate of CO is significantly higher for anthracite coal than bituminous coal, although this was not the case in the limited testing done for this study. Also, no correlation has been found between burn rate and CO emissions. It has also become apparent that CO emissions are dependant upon the stove design: a stove with a large grate area will have lower CO emissions than one with a smaller grate area.

Jaasma[8] concluded that CO emissions are dependant on the loading and the stage of the burn cycle. He found that, as the fuel (bituminous coal) agglomerated and swelled, the air flow through the bed decreased, causing an increase in CO emissions. All tests in the Jaasma study were done with a high volatile bituminous coal that had a medium-to-high free-swelling index.

This trend of increasing CO concentrations has not been observed during extensive tests on stoves B and C. In fact the emissions appear to decrease over time. Nor does the above theory explain why the CO emissions are higher for anthracite (which does not swell or agglomerate appreciably) than bituminous.

One difference between the two fuels was that the anthracite coal used was of a higher ash content than the bituminous. Secondly, the anthracite ash does not fall away from the remaining coal as easily as the bituminous ash does. So even though the anthracite does not swell, it is possible that it is the ash that causes a restriction in the air supply to the bed, causing higher CO concentrations.

Summary:

In conclusion it was found that emissions of particulates, extractable organics, PAH, and volatiles were higher for bituminous coal than anthracite. The style of the stove, type of fuel, and burn rate all affect the emissions. Thus when comparing overall emissions from the two stove styles, it is not clear which stove was less polluting (i.e., more efficient). Sulfur dioxide emissions are dependant upon both the firebox temperature and the alkalinity of the ash and are therefore expected to vary accordingly from test to test and stove to stove.

It should be noted that the values reported in this study represent a very small data base; thus this work should be considered a contribution to the literature in the field instead of a comprehensive evaluation of these combustion systems.

ACKNOWLEDGMENTS

The scales used in the determination of burn rate were supplied by the Fairbanks Weighing Division of Colt Industries, St. Johnsbury, Vermont. Bituminous coal was donated by Vermont Casting, Randolph, Vermont.

The participation of two Battelle staff members is gratefully acknowledged: Cheng C. Chuang for GC/MS data computation and Robert L. Livingston for gas mass spectral analyses.

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